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Article

Water Exchanges in Mediterranean Microtidal Harbours

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Abstract: Mediterranean ports feature complex layouts and exert important environmental pressures in squeezed coastal zones. They experience mild meteo-oceanographic conditions during part of the year, leading to water velocities that are close to the resolution limits of observation equipment. The paper addresses the challenge of characterising summer port hydrodynamics by designing intensive field campaigns, focused on hydrodynamic variables, such as harbour entrance fluxes. The approach was developed for three Spanish microtidal harbours with different domain sizes and one or two entrances. These elements play a key role in harbour exchanges through the entrance and the subsequent water renovation. The paper will present and discuss the meteocean data and inferred variables, such as renovation times, which is a key indicator of water quality. From this basis, the paper will discuss the changing estuarine circulation patterns and the role of upwelling and downwelling on observed water temperature peaks. The conclusions will address the role of harbour hydrodynamics in integrated coastal water quality and port engineering, particularly for ports' environmental impacts on adjacent beaches. To assess the full hydrodynamic domain, forecasting models are helpful. The continuous observations presented in this work would also help in the implementation and validation of these models.

Keywords: water exchanges; harbour renewal time; microtidal harbours; upwelling and downwelling effects; Barcelona, Tarragona and Castellón harbours

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1. Introduction

In the current context of globalised economy, maritime transport has become the main solution to sustaining the international demand for the traffic and trade of goods. Ports have, therefore, become a key element in ensuring the continuity of essential supplies on a global scale. As the main distribution centres, sea harbours play a crucial role in the world economy [1]. As a downside, the exponential growth of shipping in the last few years and the population increase in coastal regions are worsening water quality and progressively degrading marine ecosystems around the world [2]. Harbour-linked pollution threatens coastal systems' health and attractiveness, tourism, and coastal populations' quality of life [3]. Therefore, it is crucial to strike a balance between the economic and ecological interests of coastal zones, maritime transport, and ports.

Water in harbours and their neighbouring areas can present pollution problems that are caused by a variety of sources, including those arising from the regular operation of ships, such as cleaning and bunkering; from land-based sources, such as runoff; and from point sources, such as discharges resulting from accidents [4]. In parallel, water quality in harbours is also conditioned by the physical behaviour of the receiving environment, i.e., by its hydrodynamics [5] and renewal capacity [6]. The environmental impact also depends on the commercial activities carried out in the harbour domain [7]. The great variety and diversity of the locations, size, industrial activity, traffic volume, and the local meteocean conditions presents a significant challenge in providing a unified response to sustainable development and environmental protection demands [8].

The observed degradation of harbour water's quality can lead to various environmental problems, including eutrophication, anoxia, and algae proliferation. This is due to the uncontrolled discharge of organic matter [9,10], or to heavy metal aquatic pollution that is linked to the transport and resuspension of contaminated sediment in areas of high industrial activity [11,12]. However, anthropogenic discharges, such as filtrations or accidental spills, are probably the impacts that most degrade the water quality in harbours [13]; they represent the most frequent type of accident, being associated with 51% of the total number of accidents that occur [14].

This deterioration affects commercial harbour waters and can also have a negative impact on the development of activities in nearby areas, such as beaches, promenades, or yacht clubs. Therefore, it is important to draw up management and prevention plans based on a reliable characterisation and prediction of harbour hydrodynamics and the resulting water exchanges with its outer environment.

In addition, harbour domains are affected by weather events that can be extreme, such as storm surges and strong winds [15], which affect harbour infrastructures and their activity. These are expected to increase in the near future, according to climate change predictions [16,17], which will compound the challenge of characterising port impacts under accelerating sea-level rises [18,19], the enhanced vulnerability of coastal areas [20], and the stressed harbour operability [21].

Characterising and being able to predict the different variables that define the hydrodynamics in harbour domains and the water exchanges with the outer coastal zone is a critical factor for environmentally and economically sustainable decisions. The proposed hydrodynamic characterisation for restricted coastal domains must combine data obtained from numerical models [22] in situ and from remote observations [23], which would lead to a multi-source and multi-disciplinary assessment [24]. The aggregated information makes it possible to characterise harbour hydrodynamics, identifying dominant processes and patterns, which can be the basis for an integrated harbour management.

The analyses performed for Mediterranean harbours on the Spanish coast illustrate how field observations constitute an essential source of information in determining mixing and transport processes in restricted coastal domains. Recordings with enough time, spatial resolution, and coverage can support the development of predictive hydrodynamic and water quality models [5]. However, the accuracy and reliability of these models depend, to a large extent, on the quality and interpretation of the input data, as well as on their calibration and cross-validation [25].

Because of the low intensity of the observed currents, which are close to the measuring instruments' accuracy limits and associated with the micro-tidal amplitudes [26], Mediterranean coastal harbours are particularly complex to monitor and forecast, from an oceanographic standpoint. The main objective of this article is to demonstrate the importance of field observations in these domains in characterising harbour hydrodynamics and, subsequently, in calibrating operational oceanographic models [13] that support an integrated port management system. With that aim in mind, this paper will analyse the in situ meteo-oceanographic time series, applying these results to characterise harbour water renovation patterns and the associated water quality. The intensive campaigns presented will be the basis of a continuous monitoring plan for harbour domains, combining models and observations to achieve an integrated port exploitation system that considers economic and environmental aspects.

Dabra et al. (2009) [27] pointed out that the monitoring of currents in harbours is one of the most important observations, because it is environmentally relevant and also important for the operability of the harbours. This article aims to demonstrate that continuous observations in harbours can contribute to their operational management. Currently, there is a generalised use of tide gauges in harbours, however, there is a gap in meteorological and current measurements [28]. From current data taken at the harbour mouths, it is possible to estimate the renewal times and, therefore, to assess their vulnerability to pollution events in real time and on a continuous basis. Using data from measurement campaigns, this utility will be demonstrated. The calculation of renewal times to assess the quality and vulnerability of the water body is already commonly used in the analysis of bays [29], estuaries, and even harbours [30]. However, the data used in this study are from modelling, not observations.

The three harbours selected for analysis were Barcelona (large-sized and with two entrances), Tarragona (mid-sized and with one entrance), and Castellón (small-sized and with one entrance). These ports present complementary differences in terms of surface area, shape, and the number of mouths, as described below. These three harbours are located in the same western Mediterranean Sea and are under similar meteocean conditions due to their proximity to each other and their microtidal ranges. However, each harbour presents a distinct hydrodynamic behaviour, providing a basis on which to generalise the results from this study to other microtidal harbours.

2. Materials and Methods

2.1. Study Area

The three harbours analysed in this study are located on the Spanish coast, in the north-western Mediterranean Sea (Figure 1). This is a microtidal environment, with mixed but predominantly semidiurnal tides and tidal ranges of approximately 20 cm [31]. Meteorologically speaking, it is subject to local high and low atmospheric pressure systems, controlled by the orography of the region, which also determines the spatial distribution of winds. These are usually classified as low- and medium-low intensity, although extreme synoptic events can occur [32].

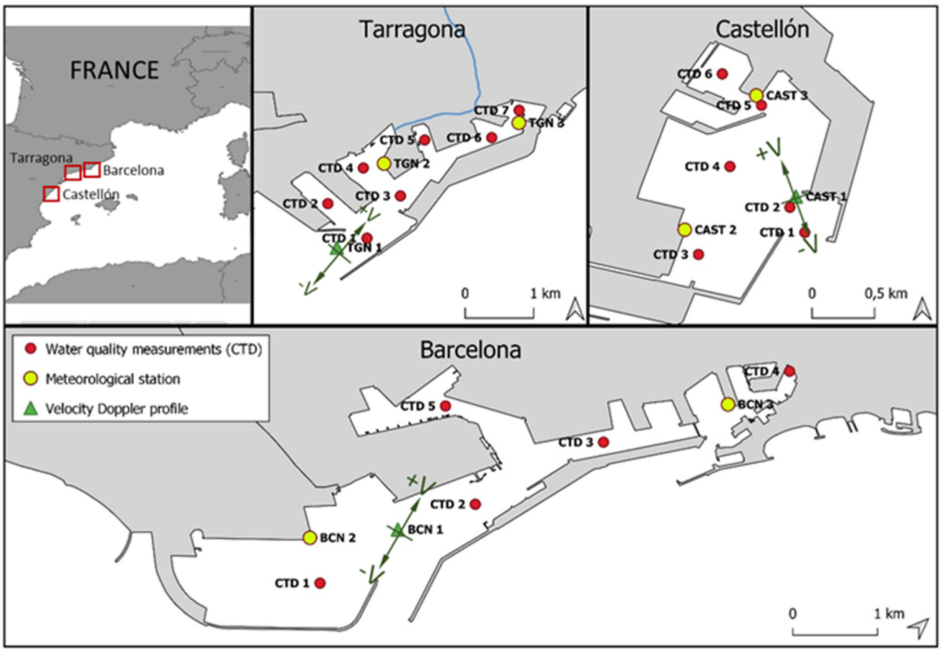

Figure 1. Maps of harbour case studies. Left upper inset shows the ports' locations. The other insets show the layout of Tarragona, Castellón, and Barcelona Ports. Coloured and numbered circles indicate locations of measuring sites. Green triangles correspond to current metre deployments, yellow dots indicate meteorological and sea-level stations, and red dots show the location of CTD (Conductivity, Temperature y Depth) profiles.

Table 1 summarises the main characteristics of the harbours as follows: size, depth, and entrance features. Barcelona harbour is the largest and has two mouths, connected by the main channel and plenty of docks of different sizes. Tarragona harbour is the second largest, more rectangular, and has varying widths from 200 to 1000 m. Finally, the harbour of Castellón is squarer, and the smallest of the three studied. A more detailed description is given below.

Table 1. Main geometrical characteristics of the studied harbour domains.

Harbour	Water Surface (km^2)	Depth (m)	Mouth Section (m^2)
Barcelona	7.6	8–20	(S mouth) 8.480 (N mouth) 1.740
Tarragona	3.8	10–20	11.400
Castellón	2.4	4–16	5.882

2.1.1. Barcelona's Harbour

Barcelona's harbour is approximately 10 km long and 2 km wide, with a longitudinal axis, rotated clockwise approximately 30° with respect to north. It presents a complex geometry that includes several channels and basins of various shapes and sizes, with depths varying between 8 and 20 m [24]. The harbour waterbody is connected to the open sea through two mouths: the north mouth is approximately 145 m wide, whereas the south mouth is approximately 530 m wide. Urban runoff discharges occur inside the harbour and can be larger than 50 m^3/s over 1–2 h in extreme rain conditions [30]. In normal conditions, the mean freshwater discharge from runoff and precipitation has been estimated at 0.2 m^3/s, according to the data provided by the harbour of Barcelona. Especially in spring and autumn, the harbour waters can be influenced by the freshwater plume from the Llobregat river, a small (average 19 m^3/s) river, with its mouth located a few kilometres downcoast from the harbour's southern mouth [30]. A summary of data, observational periods, and recording intervals during the Barcelona harbour campaign is presented in Table 2.

Table 2. Summary of data measured at the stations shown in Figure 1, corresponding to the Barcelona harbour campaigns, indicating observation periods and data recording intervals.

Station Name (ID)	Registered Variables	Observational Period	Time or Space Resolution
BCN 1	Currents, sea level, and bottom temperature	3 June–4 September	10 min
BCN 2	Atmospheric pressure, wind, and sea level	3 June–5 September	10 min
BCN 3	Sea level	3 June–5 September	10 min
CTD	Temperature and salinity	26 June (first)–12 September (last)	0.25 m

2.1.2. Tarragona's Harbour

Tarragona's harbour is approximately 4 km long and has a width that varies from 200 m to 1 km, with a longitudinal axis oriented to the north-east and depths of between 10 and 20 m [33]. It is the region's main petrochemical harbour and an important industrial and commercial maritime hub [34]. It is connected to the open sea by a 570 m wide mouth at the southern end of the harbour. Urban runoff is discharged inside the harbour domain [35], both directly through outfalls and indirectly via the Francolí river, the mouth of which is inside the harbour. The river's flow shows strong seasonal behaviour, with a summer monthly average 6 km upstream from the mouth of 0.2 m^3/s, increasing to 1.4 m^3/s during the winter, with maximum flows of up to 80 m^3/s [33]. The joint average freshwater discharge from the outfalls and river mouth is estimated at 0.8 m^3/s [35]. A summary of data, observational periods, and recording intervals during the Tarragona harbour campaign is presented in Table 3.

Table 3. Summary of measured data at the stations, shown in Figure 1, corresponding to the Tarragona harbour campaigns, indicating observation periods and data recording intervals.

Station Name (ID)	Registered Variables	Observational Period	Time or Space Resolution
TGN 1	Currents, sea level, and bottom temperature	11 April–19 September	10 min
TGN 2	Atmospheric pressure, wind, and sea level	11 April–19 September	10 min
TGN 3	Atmospheric pressure, wind, and sea level	11 April–19 September	10 min
CTD	Temperature and salinity	12 April (first)–20 September (last)	0.25 m

2.1.3. Castellón's Harbour

The harbour of Castellón is approximately 2.4 km long and 1.2 km wide, with depths ranging from 4 to 16 m. The harbour waters are connected to the open sea through a 364 m wide mouth. Unlike the other two harbours in this study, there is hardly any literature or data referring to the Castellón harbour's hydrodynamics or to the freshwater discharges into the harbour domain. Because of this, the freshwater contribution from land (estimated at 0.06 m^3/s) has been calculated using the balance between inflow and outflow rates at the mouth. A summary of data, observational periods, and recording intervals during the Castellón harbour campaign is presented in Table 4.

Table 4. Summary of measured data at the stations, shown in Figure 1, corresponding to the Castellón harbour campaigns, indicating observation periods and data recording intervals.

Station Name (ID)	Registered Variables	Observational Period	Time or Space Resolution
CAST 1	Currents, sea level, and bottom temperature	11 June–17 September	10 min
CAST 2	Atmospheric pressure, wind, and sea level	10 June–17 September	10 min
CAST 3	Atmospheric pressure, wind, and sea level	10 June–17 September	10 min
CTD	Temperature and salinity	11 June (first)–18 September (last)	0.25 m

2.2. Field Campaigns

Three field campaigns, one in each harbour, were carried out between April and September 2019 to characterise the main meteo-oceanographic forcings and harbour hydrodynamic responses that control the harbour–open sea exchanges and, thus, the resulting water quality in the harbour and adjacent beaches. The first of these campaigns monitored the Tarragona harbour (April 2019), followed by Barcelona (June 2019) and, finally, Castellón (mid-June 2019). All campaigns ended during September 2019 and included time series of current profiles, sea levels, temperatures, salinity, and meteorological data in the three harbours. Moreover, at the beginning and end of the campaigns, vertical temperature and salinity profiles were measured using a CTD at different locations inside the harbour domains. These campaigns were part of a series of campaigns carried out in 11 Spanish harbours in the framework of the Samoa 2 project. All the harbours studied, excluding Barcelona, have only one mouth, therefore, for financial reasons only one current meter was installed. Due to the fact that the campaigns were carried out in summer, the results and conclusions obtained are only comparable and applicable to other summers. However, the summer months in the harbours of the Mediterranean coast are critical because of their low energy conditions, which could lead to a significant deterioration in water quality. Therefore, it is essential to focus studies and work on these summer months.

Meteorological and sea-level data were recorded by meteorological stations equipped with a tidal gauge, located in the central area of the harbours. All the time series had a sampling interval of 10 min. At the beginning and the end of each campaign, vertical profiles of water quality parameters, temperature, and salinity were measured at several locations in the harbour, using a SeaBird 19 plus CTD sensor (Sea-Bird Electronics, Bellevue, WA, USA), registering data every 0.25 m. Because of technical issues, the CTD profiles were not acquired at the beginning of the Barcelona harbour campaign, being replaced by one of the CTD regular profiling campaigns carried out bimonthly by the harbour authority.

Finally, time series of waves and currents were obtained using Doppler profilers (ADCP). In Tarragona and Castellón, an AWAC was deployed at the harbours' entrances, providing waves and vertical current profiles with a 0.5 m resolution every 10 min. Due to heavy maritime traffic in Barcelona, it was not possible to deploy the ADCP (a SIGNATURE1000 model, Nortek, Rud, Norway) at the main harbour mouth, so it was instead placed at the intersection of this entrance with the main entrance channel (see Figure 1). In all cases, a temperature probe was installed in the structure housing the current metre, providing measurements of the bottom water's temperature

To simplify the circulation analysis, the measured velocities were projected into parallel and normal directions to the harbours' mouths. In subsequent analyses, the v-component of the water velocity was positive when flowing into the harbour and negative when flowing out of it. To assess circulation patterns, a daily average for each registered water column layer was calculated for the entire period, which led to an average layer value of the whole observational period.

2.3. Renewal Times

Water renewal time (RT) is a key indicator of water quality in harbours, and it can be defined as the average time that a water particle remains inside the harbour domain. This study assumes that water exchanges occur only through the harbour mouth, ignoring dyke permeability or overtopping. Renewal times are then calculated from inflow and outflow balance in each harbour. Once the net flow rate is obtained, the water renewal time can be estimated as the ratio between the total harbour water volume over the net inflow or outflow rate [36]. This first estimate of RT corresponds to the time required for the entire mass of harbour water to be replaced by outer sea water [37].

The net water inflows and outflows in harbours are mainly controlled by density differences, driven by salinity gradients [23]. Two of the various methods available in the scientific literature have been used to calculate these water exchanges. The first one is an approximation of the stationary box model [38], which mainly calculates salinity differences caused by freshwater inputs from harbour rivers, surface runoff, and rainfall. The model assumes a stationary system, in which the water volume and salinity within the harbour are constant over the analysis period. The size of the harbour mouths has been estimated from harbour reports and satellite imagery measurements. The analysed harbours do not have siltation problems at the mouths and, therefore, no dredging operations are done. This approach was applicable to Tarragona and Castellón, with one single entrance, however, it could not be used for the Barcelona harbour, where the presence of two entrances hinders the assumption of stationarity.

Application of the box model requires separating the harbour water into boxes (upper and lower in this case), defined from the registered Doppler current profiles and the depth at which the mean current changes direction (example diagram in Figure 2). This approach was well suited to the Tarragona and Castellon harbours because the dominant circulation pattern can be classified as estuarine positive. Once the boxes have been defined, the salinity data from the CTD campaigns are used to estimate the average salinity per box, defining surface freshwater inputs from available (climatic) information. This analysis obtained a mass balance for water and salt, using Equations (1) and (2), based on the days on which CTD campaigns were carried out.

$$Q_1 = Q_2 + R \tag{1}$$

$$Q_1 \times S_1 = Q_2 \times S_2 \tag{2}$$

where Q_1 is the surface outflow, Q_2 is the bottom inflow, R is the total freshwater input, S_1 is the salinity in the surface box, and S_2 is the salinity in the bottom box.

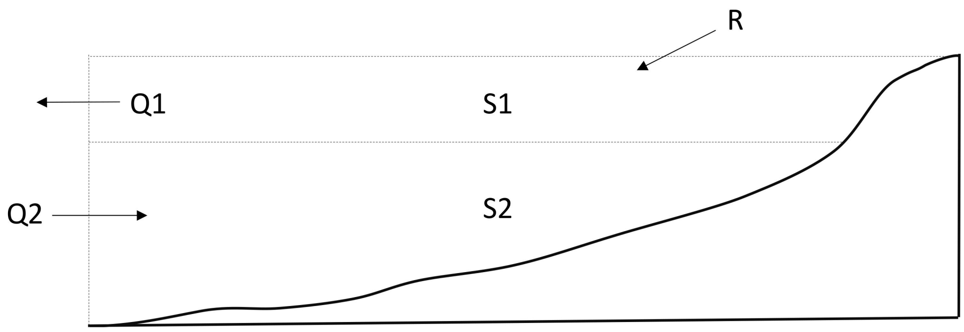

Figure 2. Box model chart applied to estimate renewal times in the harbours of Tarragona and Castellón, which comply with this circulatory pattern, typical of positive estuaries.

The second method used to estimate RT and the associated in and outflows, was based on the daily averages of the Doppler data [39]. The daily-averaged current profiles were then analysed to determine the depth at which the flow changes direction, defining again an inflow and an outflow layer. By multiplying the mean velocity by the section of each layer at the harbour mouth, the total water inflow and outflow through the harbour entrance was estimated. An example of that applied procedure is shown in Figure 3. In the particular case of Barcelona's harbour, where only one Doppler was operative near the main southern mouth, the flow of the northern entrance was calculated from a mass balance considering the freshwater input from land and the flows calculated for the southern mouth. The obtained results were compared with those obtained from the box model, which provided a more robust estimation of flows and RTs for the Barcelona harbour.

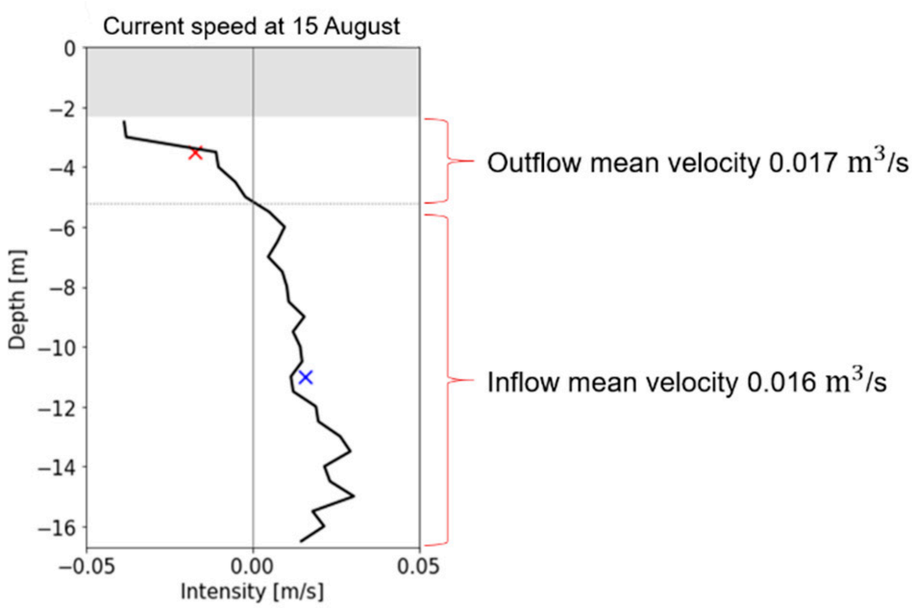

Figure 3. Vertical profile of the time averaged velocities at the Castellón harbour (in black). Averaged outflow (in red) and inflow (in blue) velocities, according to the second proposed approach.

It is important to point out that the simplifications inherent in the described methods (e.g., approximate mouth section areas, and uniform and stationary flows at the mouth) introduced further uncertainties to the estimated flow rates and renewal times. Because of this, the results presented must be considered as an approximation to the real behaviour of the harbour system.

3. Results

Any application of harbour circulation results to the integrated management of port activities requires a robust knowledge of the relation between meteocean forcings and harbour hydrodynamic responses, which include the renovation times, the domains affected, the trajectories, and the cumulative concentrations. Figure 4 presents the simultaneous evolution of meteocean drivers, together with harbour circulation responses in a single plot.

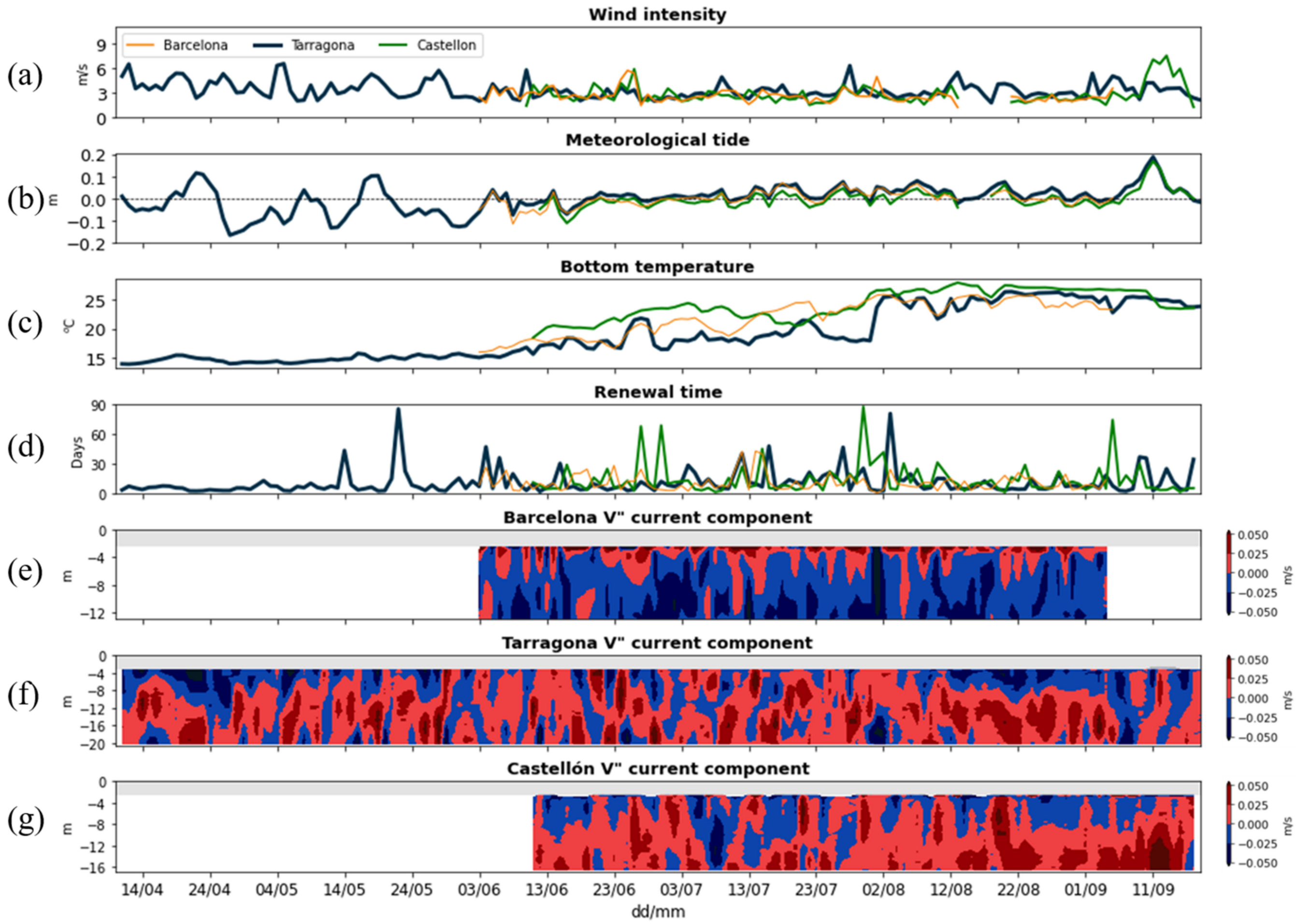

Figure 4. Time series (24 h filtered) of meteocean drivers from wind and tidal observations at Barcelona, Tarragona, and Castellón harbours, together with some of the more relevant circulation responses. From top to bottom: (**a**) wind speed, (**b**) meteorological tide, (**c**) bottom temperature, (**d**) renewal time and (**e**–**g**) v-component of the current velocity.

The upper time series in Figure 4 presents the wind recorded at weather station number two in each harbour. The series has significant similarities regarding the strongest and weakest meteo events. The corresponding wind roses are shown in Figure 5. In the Barcelona harbour (Figure 5a), the prevailing winds during the campaign came from the south and west, although the most energetic were mainly from the north-east and the south-west, with the maximum intensities, in general, approximately 10 m/s. In Tarragona (Figure 5b), the prevalent winds throughout the campaign blew from the north and the south-east, while the strongest winds were from the south-west, with maximum speeds of 11 m/s. Regarding the Castellón harbour (Figure 5c), the most frequent winds were those from the north-west, while the strongest winds came from the north-east, typically with speeds between 9 and 13 m/s.

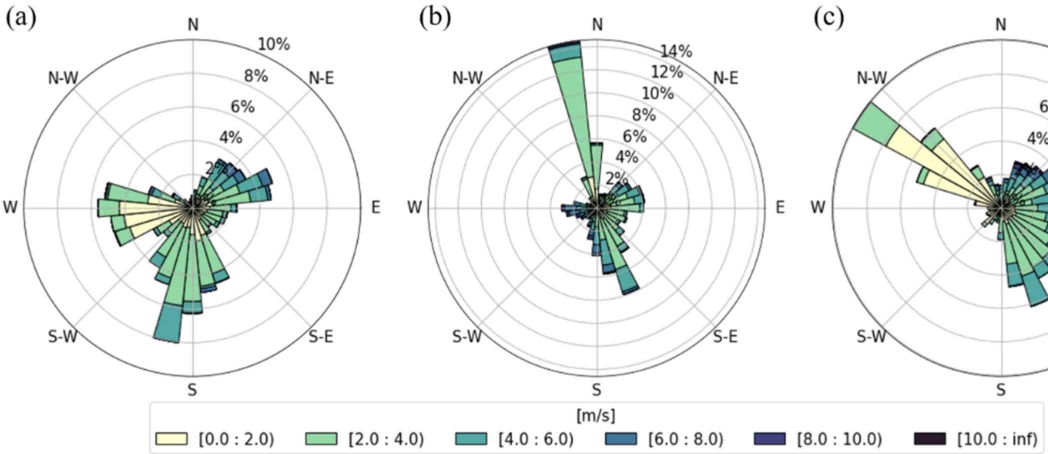

Figure 5. Wind rose diagrams from Barcelona (**a**), Tarragona (**b**), and Castellón (**c**) harbours. Concentric circles represent the percentage of occurrence, colours denote wind speeds in metres per second, and directions are "winds coming from".

Because of the local topographic control over the wind fields there were marked discrepancies in wind direction among the three harbours. However, the main wind directional sectors were north-east and south-west in all three cases during the most extreme wind events.

3.1. Sea Level

To examine the sea levels inside the harbours in greater detail, a harmonic analysis of the tides was carried out and produced the following three results: the original sea-level component (observed values); the component corresponding to the astronomical tide; and the residue or meteorological tide, which is the result of subtracting the first two and represents the elevation of the sea level that is caused by variations in the atmospheric pressure and meteorological phenomena.

The meteorological tide (Figure 4b) shows small sea-level variations, with oscillations between 10 and 20 cm. The measured sea levels were very similar in all three harbours, confirming the regional patterns that dominate sea-level variations, although local hydrodynamics will depend on the harbour geometry and the mouth orientation with respect to the prevailing meteocean conditions.

3.2. Water Bottom Temperature

Concerning the water temperatures at depth (Figure 4c), a generalised increase was observed in the three harbours that was simultaneous to the increase in the atmospheric temperature (not shown), which is characteristic of the summer months. This pattern can, thus, be associated with the seasonal variations in temperature. The highest values were recorded in the Castellón harbour, probably because of its smaller size, which enables a more efficient warming of the harbour waters. Regardless of size, the Barcelona and Tarragona time series also showed occasional abrupt temperature changes that will be analysed later.

3.3. Vertical Profiles of Temperature and Salinity

The sections shown in Figure 6a,b present the results for the two CTD campaigns carried out in each harbour. In the first campaign (Figure 6a), cold and saline waters were observed near the seabed, with warmer waters at the surface. In the case of Barcelona, in terms of horizontal distribution, colder and saltier water was observed near the surface, at stations close to the northern entrance, indicating that open sea water was entering the harbour through the northern mouth at the time of the campaign. Figure 6b shows the situation at the end of the campaign (September), in which the temperature and salinity distributions within the harbour domains appeared to be quasi-homogeneous, without any relevant vertical or horizontal gradients. In the particular case of Barcelona, however, there was a small horizontal temperature gradient towards the inner part of the harbour. It is apparent that the differences in the horizontal distributions between all the studied harbours were due to morphological differences, such as harbour size, the number of mouths, and the entrance orientation. The Figure 4c show the location of the analysed section (the red dot corresponds to the beginning of the section).

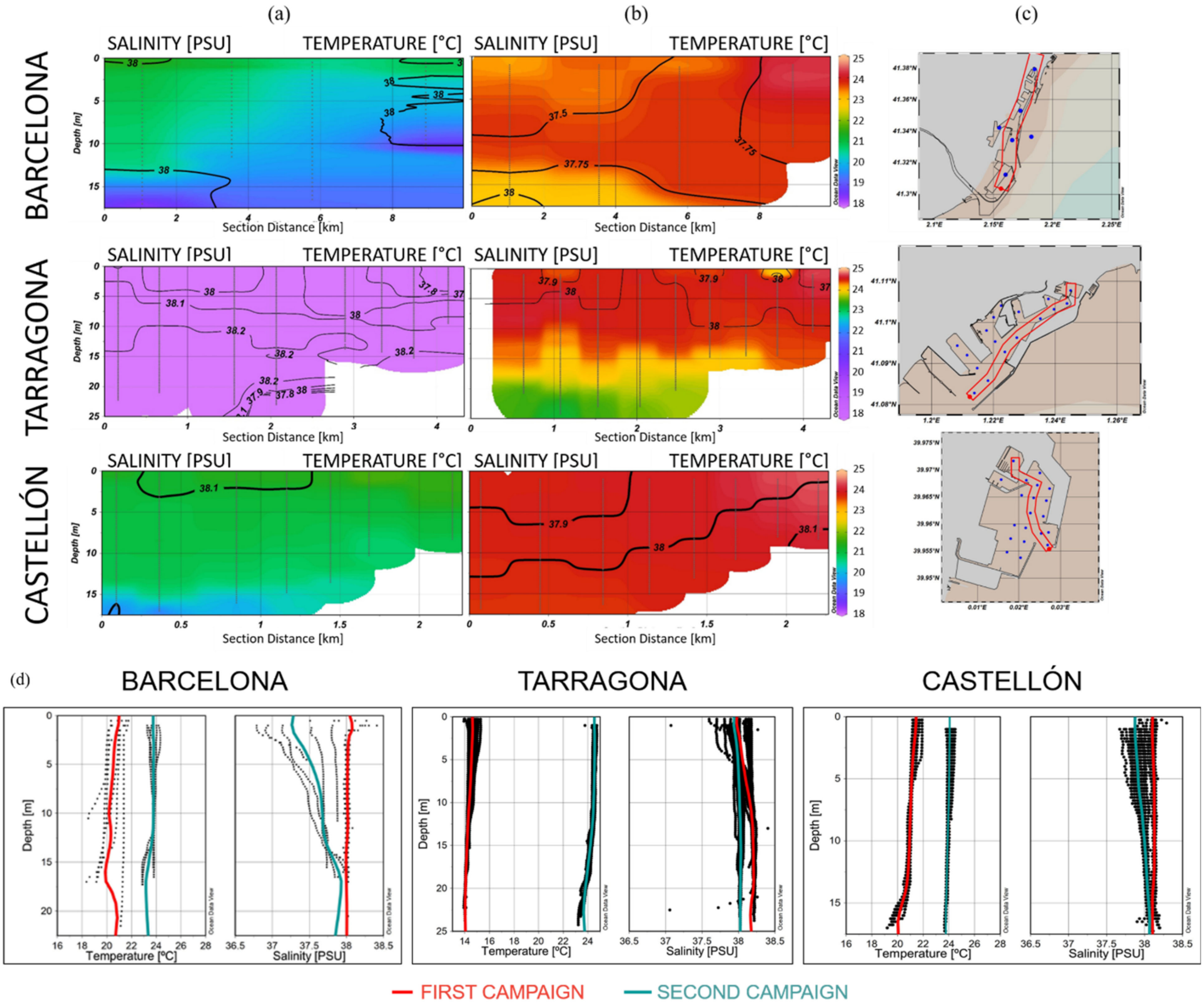

Figure 6. Temperature (°C) and salinity (PSU) sections (columns (**a**) and (**b**)) and profiles in Barcelona, Tarragona, and Castellón harbours (line **d**). In the presented sections, the colour bar shows temperature values and black lines show salinity values. Profiles in red correspond to the average of the first campaign's data, while profiles in blue correspond to the average of the last campaign's data. (**c**) is the location of the analysed section.

The temperature profiles registered at the three harbours (Figure 6d) showed the following two groups of clearly differentiated profiles: a group of cooler water data, corresponding to the CTD measurements at the beginning of the campaigns; and a set of warmer profiles, representing the higher temperatures measured in September. This increase in temperature is common during the summer months and features slightly higher water temperatures near the surface and colder waters at depth. Such patterns were more marked at the beginning of the campaigns, showing the existence of a seasonal gradient that had almost disappeared by September. Comparing the profiles of the Barcelona and Castellón harbours (both campaigns started within a few days of each other), it can be observed that the thermocline is better-defined in the case of the Castellón harbour. This may be due to the lower intensity of the water dynamics for the smaller-sized harbour. The observed seasonal stratification prevents the vertical mixing of the water column, worsening the surface water quality during the summer months. The lowest surface salinity values occur in September, which could be a consequence of freshwater inflows into the harbour, which are associated with flash floods after the summer. The resulting excess of freshwater input drives an enhanced seawater flow into the harbour at the lower part of the water column, although the gradients remain bounded.

3.4. Vertical Current Profiles

The current velocity profiles (Figure 7), derived from the averaged velocities in each measurement layer, showed a two-layer circulation in all three cases, which was persistent during the whole study period. In Barcelona (Figure 7a), a surface layer of approximately 4 m was observed flowing towards the northern part of the harbour (positive values), with a thicker, deep layer flowing towards the southern basin (negative values). In contrast, in Tarragona and Castellón (Figure 7b,c), the opposite distribution was observed, with surface currents flowing out of the harbour and seawater entering through the deeper layers. Because of the small intensity of the observed currents, only averaged values have been presented, since they are the only ones suitable for further comparisons and cross-calibration.

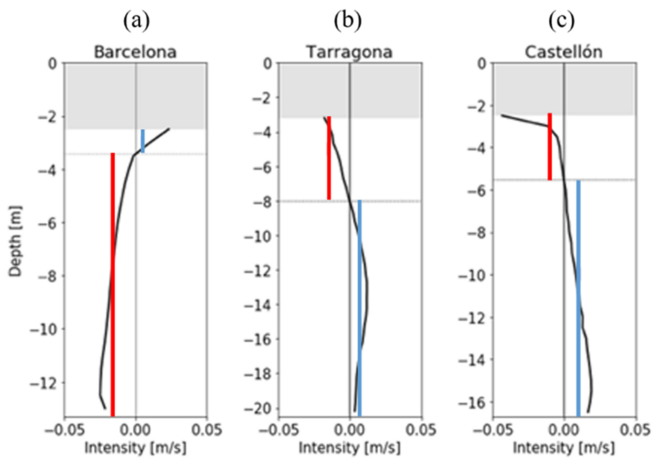

Figure 7. Time-averaged vertical profiles measured in the Barcelona (**a**), Tarragona (**b**), and Castellón (**c**) harbours (in black). Averaged outflow velocities (lines in red) and averaged inflow velocities (lines in blue). The ADP location is shown in Figure 1.

3.5. Flows and Renewal Time

The box models (the method first proposed in this study) indicated a positive estuarine circulation, where denser seawater with higher salinities flow into the harbour near the seabed and where lighter waters flow out of the harbour near the surface. In the case of Tarragona (Table 5), the inflow and outflow rates were lower at the beginning of the campaign, while in Castellón, they were higher at the beginning, illustrating the local control of harbour geometry and mouth dimensions.

Table 5. Flows and renewal times (RT) calculated for Tarragona and Castellón harbours, derived from the box model proposed in the paper.

Harbour	Campaign	Outflow	Inflow	Renewal Time
Tarragona	First	247.0 m^3/s	246.2 m^3/s	3 days
	Second	768.1 m^3/s	767.3 m^3/s	1 day
Castellón	First	540.6 m^3/s	540.5 m^3/s	1 day
	Second	21.3 m^3/s	21.2 m^3/s	14 days

The harbour waters' renewal times grew when flows got weaker, as was expected. It is important to point out that between 9 and 11 September, just before the second CTD campaign in Barcelona, which started on 12 September, there was an episode of storms and torrential rains, which was produced by an exceptional CAP (cold air pool) that may have contributed to the enhanced input of freshwater. This input should have generated a stronger estuarine circulation, reducing the harbour water renewal times. In a similar way, the salinities measured on 11 June in Castellón might be affected by a precipitation episode that occurred between 5 and 11 June.

To assess the sensitivity of the inflow and outflow rates, together with the harbour renewal times (RT), they were also estimated using the second proposed method, based on the velocities provided by the Dopplers and the two-layer circulation pattern discussed in the previous sections. The results are presented in Tables 6 and 7.

Table 6. Flows and Renewal Times (RT) calculated for Tarragona and Castellón harbours from measured Doppler velocities during the field campaigns.

Harbour	Quantity	Outflow	Inflow	Renewal Time
Tarragona	Minimum	2 m^3/s	0 m^3/s	2 days
	Maximum	336 m^3/s	166 m^3/s	85 days
	Average	108 m^3/s	54 m^3/s	11 days
Castellón	Minimum	0 m^3/s	1 m^3/s	2 days
	Maximum	212 m^3/s	105 m^3/s	87 days
	Average	41 m^3/s	30 m^3/s	34 days

Table 7. Flows and Renewal Times (RT) calculated for Barcelona harbour from measured Doppler velocities during the field campaigns.

Harbour	Quantity	South Mouth		North Mouth	Renewal Time
		Outflow	Inflow		
Barcelona	Minimum	1 m^3/s	0	0.7 m^3/s	1 days
	Maximum	232 m^3/s	159 m^3/s	232 m^3/s	43 days
	Average	51 m^3/s	52 m^3/s	45 m^3/s	18 days

4. Discussion

The water circulation inside harbours controls the water quality and the impacts on the port domains and the adjacent beaches. Under macrotidal conditions or strong wind events, the water circulation may play an important role in harbour exploitation by affecting the entrance and berthing manoeuvres that determine harbour exploitation and performance, and by interacting with the harbour layout and, therefore, the design of the harbour infrastructure.

This paper addresses microtidal harbours, which experience very weak circulation patterns during a significant part of the year and that have velocities of order 1 to 5 cm/sec inside the port domain. To enable a cross-validation of such limited velocities–close to the resolution limit of observational equipment and numerical simulations–all the harbours analysed in this study are located in the same Mediterranean region, which are subject to similar atmospheric and oceanographic forcings, as supported by the recorded data. The most distinctive driver was the wind field. This is strongly conditioned by the local orography and buildings but shows similar characteristics in all three harbours (Figure 4a) for the most intense meteo events. This similarity under an energetic episode, was proven by high correlations in the wind direction for the neighbouring ports (Barcelona–Tarragona: 0.8 and Tarragona–Castellón: 0.7), while the correlation was much lower for the two ports at the north and south ends of the regional area, which are approximately 230 km apart (the Barcelona–Castellón correlation was 0.1). Previous studies have shown significant spatial variability within the largest harbours, such as Barcelona, due to the local coastal mountain of Montjuïc and the nearby buildings [40]. From the deployment of the meteo stations it appeared that, in the performed campaign, the data should not be significantly influenced by the nearby buildings; however, for channelled, jet-like winds, as was the case in the Tarragona harbour, there may be appreciable differences between the local stations. This indicates the importance of designing high-resolution meteo campaigns that consider the local topography, since the local winds drive the harbour circulation and the exchanges with the adjacent coastal sea. In the particular case of the Tarragona harbour–which is affected by channelled winds and, thus, more sensitive to local effects–the data from station TGN2 (see Figure 1) were considered as the reference for the port domain. Station TGN3 is more influenced by the surrounding buildings, and so provides information on the local effects.

4.1. Upwelling and Downwelling Events

The evolution of the bottom temperatures in the monitored harbours (Figure 4c) showed some abrupt changes, which were more marked for the larger domains, such as Barcelona and Tarragona. The first one occurred on 24 June (Figure 8), when the temperature increased from 16.5 °C to 20 °C and 22 °C (Barcelona and Tarragona, respectively) in 48 h. It maintained its growth during a two-day period and then declined. The second abrupt change (Figure 9) showed a 3 °C decrease in approximately 12 h on 23 July, falling from 23 °C to 20 °C in Barcelona, and from 21 °C to 18 °C in Tarragona. The third selected episode (Figure 10) occurred in Tarragona Harbour on 31 July, when the temperature rose by almost 8 °C in 24 h. These sharp gradients were attributed to water mass and the impulsive exchanges between the warmer surface layer and the cooler layer near the seabed, where, because of the physical constraints imposed by the harbour structures, there are important interactions–even for moderate meteocean driving factors.

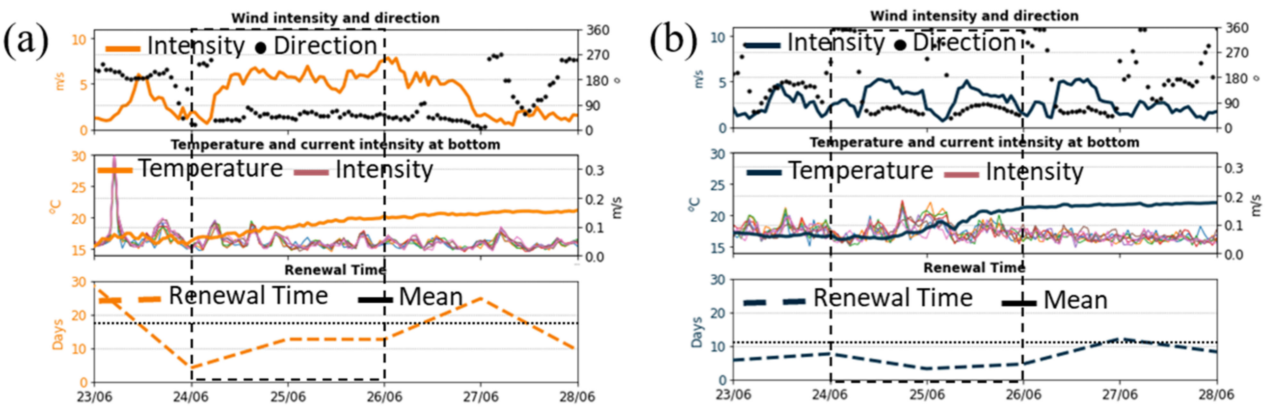

Figure 8. Detailed evolution of wind driving and harbour water responses during the first episode of an abrupt temperature increase in the Barcelona (**a**) and Tarragona (**b**) harbours. Top row: wind intensity (solid line) and wind direction (black dots). Middle row: temperature (thick line) and current speed near the seabed (the thin coloured lines represent the intensity in the deeper layers). Bottom row: turnover times (the black line is the average turnover time of the harbour). The dashed black squares correspond to the day of downwelling.

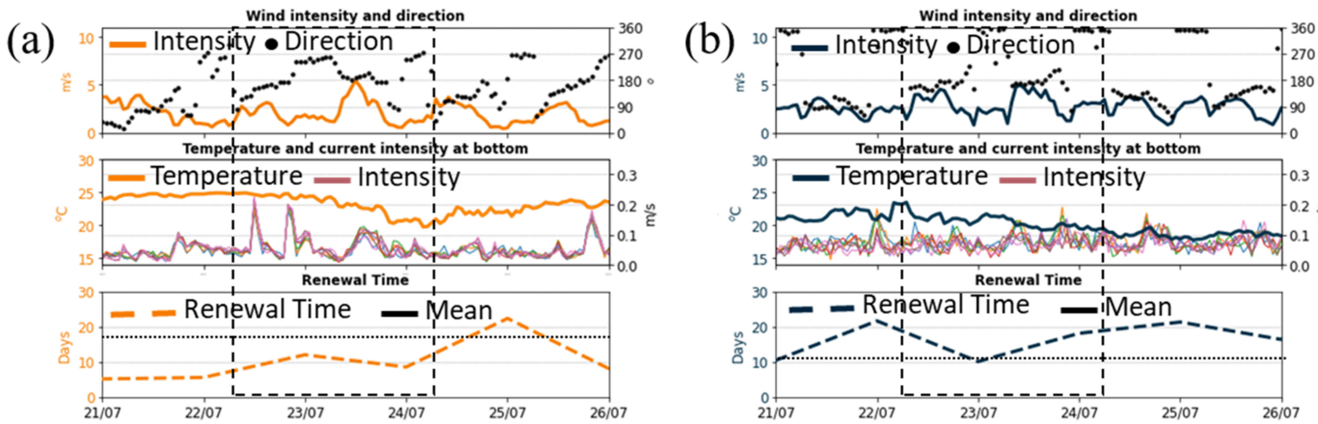

Figure 9. Detailed evolution of the second episode of abrupt temperature increases in Barcelona (**a**) and Tarragona (**b**) harbours. Top row: wind intensity (solid line) and wind direction (black dots). Middle row: temperature (thick line) and current speed near the seabed (the thin coloured lines represent the intensity in the deeper layers). Bottom row: turnover times (the black line is the average turnover time of the harbour). The dashed black squares correspond to the day of upwelling.

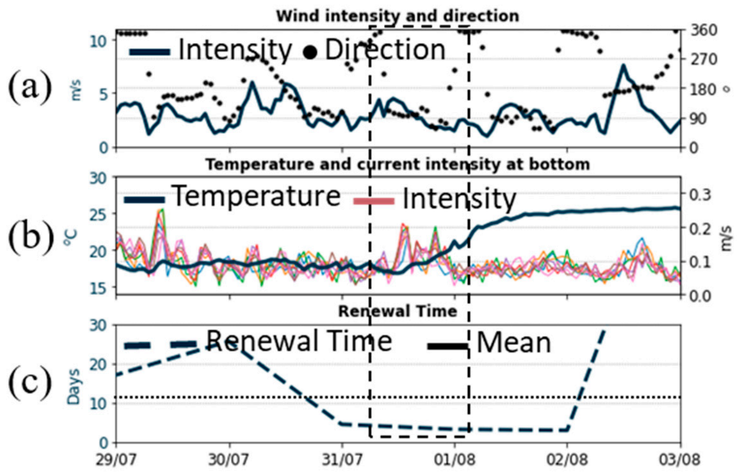

Figure 10. Detailed evolution of the third episode of abrupt temperature increases in Tarragona harbour. Line (**a**) wind intensity (solid line) and wind direction (black dots). Line (**b**) temperature (thick line) and current speed near the seabed (the thin coloured lines represent the intensity in the deeper layers). Line (**c**) turnover times (the black line is the average turnover time of the harbour). The dashed black squares correspond to the day of downwelling.

Focusing on the first episode of a regional temperature increase in Barcelona and Tarragona (Figure 8), it was observed that it coincided with episodes of north-easterly winds and stronger currents at depth (0.05 m/s in Barcelona and 0.08 m/s in Tarragona). The winds from the north-east, with an eastern component, favour downwelling processes along the Catalan coast, implying that the action of north-easterly winds enhance the outflow of warmer harbour bottom waters (because of the restricted volume to be heated). Such an outflow increased the near-bed water temperature during this wind episode.

During the second analysed event (Figure 9), the wind blew from the south-west, which induced upwelling processes by driving the surface seawater from inside the harbour towards the outside, at speeds of approximately 0.08 m/s in Barcelona and 0.06 m/s in Tarragona. This upwelling favoured the entrance of deeper, colder waters, which decreased the temperature measured near the seabed.

In contrast, during the third event in the harbour of Tarragona (Figure 10), the wind was again from the east, with an increase in near-bed current velocity (average of 0.1 m/s) and a simultaneous rise in bottom temperatures, which, again, indicated a downwelling episode.

The temperature time series in the Castellón harbour (Figure 4c) showed no evidence of upwelling or downwelling events. This could be due to the limited horizontal extent and depth in the domain, which are insufficient to develop a harbour response to upwelling or downwelling processes. Moreover, the very rectangular (regular) harbour geometry does not favour the channelling of currents towards a specific direction, thus, hindering the penetration of outer waters, which will seldom reach the measuring station that is located 1.2 km from the inner harbour wharfs.

Previous studies showed intense upwelling and downwelling zones along the wharves of the Barcelona harbour [24] supporting the role of these processes in water exchanges in the case of the Barcelona harbour, which features two harbour entrances. The observed temperature variations can be affected by factors such as in-harbour freshwater discharges or geometrically induced circulation patterns (for instance, the two mouths and central harbour channel), all of which are modulated by the prevailing meteocean conditions.

Upwelling and downwelling episodes influence harbour renewal times, as illustrated by the analysed downwelling episodes (24 June and 31 July), where renewal times were significantly lower than the harbour average (11 days for both episodes). Upwelling episodes (23 July) produced the opposite effect because downwelling favours water outflow from the harbour, thus reducing renewal times. However, upwelling, which is associated with the inflow of outer sea waters, increases renewal times.

4.2. Renewal Time Assessment and Variability

The renewal times and the underlying exchange flows are key indicators for harbour water quality, which impact on the adjacent beaches, contingency plans for pollution events, and the integrated management of port–coast interactions and their effect on activities and infrastructures. For the Barcelona case, the presence of two mouths clearly favoured water renewal, compared to the Tarragona and Castellón harbours (Tables 6 and 7) that have only one mouth. In addition, the existence of a main channel in Barcelona and Tarragona leads to stronger currents, thus increasing the outflow and shortening the water renewal times, which improves the water quality inside the port but increases the risk of water quality degradation on the adjacent coasts. All other factors being equal, the domain size determines the level of constraint and control renovation, with Castellón (the smallest harbour considered) having the highest average renewal time and lower flow rates.

As can be seen in Figure 11, in all cases the renewal times presented high variability for Mediterranean microtidal conditions. This figure shows a comparison between the renewal times estimated by the box model (colour points) at the beginning and at the end of the field campaigns and those calculated from the measures' (Doppler current meter) velocities (coloured lines).

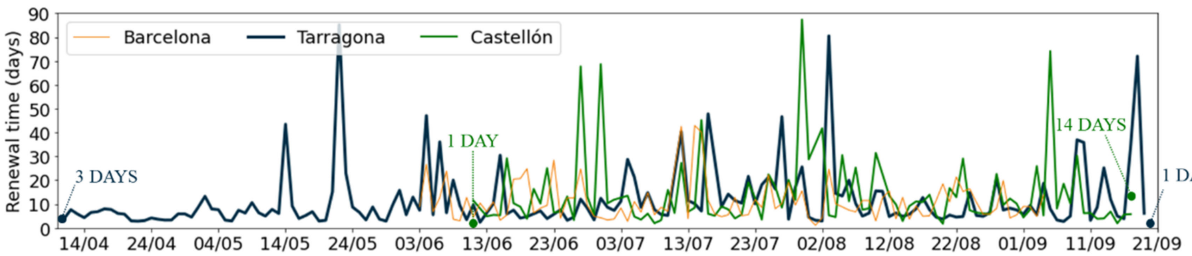

Figure 11. Sample time series of renewal times (in days) for Barcelona (orange line), Tarragona (blue line), and Castellón (green line) harbours, estimated by box models and from the recorded velocity data.

As shown in Figure 11, the typical water renewal times in all the harbours are below three weeks (approximately 25 days) but can reach much higher values on particular dates, exceeding 80 days in Tarragona and Castellón. The origin of these peaks was explored for the five days with the highest renewal times at each harbour, analysing meteocean conditions and harbour hydrodynamic responses during those events.

By analysing the mean wind intensity and the atmospheric pressure, presented in Table 8, it is apparent that the days with the highest renewal times correspond to a stable atmospheric situation, under the typical summer season's anticyclone patterns and weak winds. Furthermore, these anticyclone periods feature low current velocities that increase the renovation times–which are well above previous estimations, ranging between 8 and 18 days for the Barcelona harbour, depending on wind conditions [30]. The result of the present analysis, approximately 18 days on average during the study period, coincides with the upper limit of previous studies. In the case of Tarragona, renewal times varied between 10 (innermost areas of the harbour) and 2.5 days (areas near the mouth), which agrees with the previous literature [4]. However, the very limited discharges from the Francolí river inside the harbour during the summer season (0.54 m^3/s on average) may further increase renovation times beyond 10 days. The 11 days obtained in this analysis are, thus, consistent with the upper band of previous estimations. Finally, no previous studies have been published on water renewal times for the Castellón harbour, preventing any comparison between the existing literature and the estimations obtained here.

Table 8. Main meteocean drivers represented by atmospheric pressure and wind intensity, together with the resulting current velocity (daily averages) during the days that featured the highest renewal times in each harbour.

	Renewal Time (Days)	Date	Atmospheric Pressure	Wind (Intensity)	Wind (Direction)	Current (Intensity)
BCN	27	4 June 2019	1011 hPa	2 m/s	S	0.05 m/s
	27	23 June 2019	1014 hPa	2 m/s	S	0.08 m/s
	43	12 July 2019	1015 hPa	2 m/s	SE	0.05 m/s
	43	14 July 2019	1010 hPa	3 m/s	SE	0.06 m/s
	40	15 July 2019	1010 hPa	3 m/s	S	0.05 m/s
TGN	85	22 May 2019	1018 hPa	2 m/s	SE	0.06 m/s
	47	4 June 2019	1012 hPa	5 m/s	SE	0.06 m/s
	48	16 July 2019	1016 hPa	4 m/s	SW	0.08 m/s
	80	3 August 2019	1015 hPa	3 m/s	SW	0.05 m/s
	72	18 September 2019	1014 hPa	2 m/s	S	0.05 m/s
CAST	68	27 June 2019	1018 hPa	2 m/s	S	0.06 m/s
	69	30 June 2019	1016 hPa	2 m/s	SE	0.06 m/s
	45	15 July 2019	1010 hPa	2 m/s	SW	0.07 m/s
	87	30 July 2019	1013 hPa	3 m/s	E	0.07 m/s
	74	5 September 2019	1017 hPa	3 m/s	SW	0.07 m/s

In comparing the flow rates resulting from the box model and those calculated from the Doppler recorded velocities, some differences can be observed. It is important to note that the results of the box model correspond to two specific days, and those obtained from the Doppler velocities are the average for the entire study period. Therefore, the results obtained by the first method can be more extreme, resulting in very high or very low flows. Another reason for the discrepancies is that the box model considers only salinities and freshwater inputs, ignoring other sea-level effects on the resulting currents, such as astronomical or meteorological tides. Furthermore, all the estimations reflect calculation hypotheses, such as the average area and depth for the harbour mouths and constant velocity in the whole section. These factors introduce additional uncertainties into the estimated results, which must, thus, be handled with care, particularly under extreme meteocean conditions that may further compound the problem.

Intensive field campaigns for harbour domains are conditioned by climate and harbour exploitation requirements, which may hinder the time coverage, spatial deployment, and result representativeness. The hydrodynamic analysis, which is based on observations in the harbours, also has other limitations. In the present work, the main limitation has been the availability of a single Doppler for each harbour–in particular, for the Barcelona harbour (with two mouths); it would have been of interest to obtain data on the currents in both of them. Moreover, the shape of the mouths has been assumed, given that the profile of the mouth at depth is unknown, and it has also been assumed that only water exchanges take place at this point, i.e., that there is no permeability in the dykes of the harbour. Furthermore, the duration of the campaign only allowed us to compare the results with other summers and not with other months of the year.

The approach to intensive and multivariable campaigns that is presented here, centred around a Doppler profiler at the harbour entrance, proves the suitability of short (between 2–5 months) time series of meteocean variables to characterise harbour hydrodynamics.

The performed analyses illustrate the potential of these campaigns to establish cause–effect relationships for water renovation, temperature gradients and the exchanges with outer coastal waters. These results also highlight the need for harbour monitoring stations that record different ocean–meteorological parameters, which will provide short term benefits, such as the aforementioned cause–effect relationships, but also longer-term benefits (if the stations are maintained for several years) for climatic assessments. Longer data series will provide a more robust characterisation of seasonal and extreme event effects, determining harbour water exchanges with the outer sea for a wider range of conditions, and so facilitating the preparation of contingency plans and reducing the uncertainties in the estimated renewal times. These advances, which support the high-resolution validation of operational circulation and water quality numerical models [41], will contribute to more informed decisions for the sustainable management of harbour operations.

5. Conclusions and Recommendations

An in-depth oceanographic analysis of meteocean variables, with a resolution high enough to solve restricted harbour domains, provides quantitative support for integrated coastal–harbour operation decisions. The relation between meteocean drivers and hydrodynamic harbour responses–in terms of integrated variables, such as renovation times, or pointwise variables, such as water temperatures at critical points–can serve to develop contingency plans for environmental impacts and to advance the current knowledge on coastal hydrodynamics for restricted domains. This approach has been developed for microtidal conditions, where the driver–response relationship is harder to characterise and has been illustrated for three harbours (Barcelona, Tarragona, and Castellón) in the same climatic region within the north-western Mediterranean Sea. By means of dedicated multi-variable field campaigns, it has been possible to characterise water exchanges with the open sea, estimate renewal times, and explain abrupt gradients that may influence water quality in the harbour and adjacent beaches. The analyses have shown similar results and trends in the three harbours for variables such as wind and sea-level, confirming that they belong to the same climatic region and allowing a meaningful comparison of hydrodynamic responses.

Pointwise analyses of CTD profiles have shown the role of the harbour domain and mouth geometry in the resulting temperature and salinity distributions, which showed differences in each harbour. In Barcelona, the analysis of water temperatures near the two mouths showed an inflow of outside waters through the lower layers of the water column for the southern and larger mouth; this goes together, for volume conservation, with an outflow of water at the surface for this southern mouth. However, at the northern entrance, the coastal water enters the harbour through the entire water column. The recorded distribution of temperatures and salinities suggests that seawater regularly enters the harbour through the northern mouth and heats up as it circulates towards the southern entrance, where it only exits through the upper layers. In the case of Tarragona, lower salinities were not observed in the area near the mouth of the Francolí river, as was expected during the summer season, due to a very low river discharge during the days prior to the campaign (the average flow during the 10 days prior to the first campaign was 0.6 m^3/s and was 0.05 m^3/s prior to the second campaign). Finally, the Castellón harbour showed a very homogeneous temperature distribution in the water column during the September campaign, which was attributed to strong measured winds in the days prior to the data collection, which resulted in strong vertical mixing for the full water column.

From a comparative analysis of the current velocities in the three harbours, Barcelona, with two mouths, was the only domain that showed an averaged profile that corresponded to a negative estuarine circulation. Tarragona and Castellón, with only one mouth and, thus, a stronger constraint, presented a positive estuarine circulation. Water fluxes for the Barcelona harbour are directed towards the outside and not towards the inside of the harbour, as it was observed for the typical winter-circulation patterns described in the literature [13]. The entrance of water may condition this negative estuarine circulation through the northern mouth, which requires an outflow in the larger and deeper southern mouth under summer conditions. Due to harbour exploitation requirements, the existence of two mouths and the location of the measuring station (slightly off the entrance midpoint–Figure 1) prevented more accurate characterisations of the water exchanges under transient conditions.

As for the abrupt changes in temperature at depth, observed in the harbours of Barcelona and Tarragona, episodes of upwelling and downwelling were proposed to explain these gradients. During these events, a current intensification was recorded, which led to variations in the renewal times for the considered enhanced mixing and the reduced stratification conditions. Therefore, since upwelling and downwelling episodes occur under certain specific wind conditions, meteo patterns, as expected, acted as one of the main drivers for harbour hydrodynamics in these cases.

The estimated renewal times were comparatively higher for the Castellón harbour, considering its size (the smallest of the three), which has been linked to a higher level of constraint because it is a square domain with one mouth. This harbour's geometry leads to weaker currents than in the Barcelona and Tarragona harbours, proving that elongated shapes with a central channel and the presence of two mouths favour the intensification of harbour currents and a reduction in renewal times. However, irrespective of harbour shape, stable atmospheric situations (high atmospheric pressures and hardly any wind) result, in all cases, in higher renewal times.

A permanent and high-resolution monitoring of harbour meteocean variables, can support the development of harbour water quality indicators, providing the anticipated information to reduce risks in coastal areas due to human activities, natural hazards, and especially, port exploitation and related accidents [42]. High-resolution coastal measurements, regularly sequenced to characterise harbour hydrodynamics, can be planned within operational campaigns that supplement operational forecasting to support an integrated management of port–coast interactions and activities. The resulting information will facilitate port design and exploitation compliance with water quality legislation and the associated environmental certifications (e.g., ISOS and EMAS) for environmentally impacting operations (e.g., cleaning and dredging). These challenges require–particularly for microtidal harbours with current velocities close to the resolution limit of observational equipment and numerical models–a symbiotic combination of field measurements and high resolution-coupled models to be described in subsequent papers. Furthermore, the development of regular or continuous observational campaigns will provide benchmark datasets for model calibration, sensor intercomparisons, and optimised approaches to field monitoring that combine in-situ and remote data.

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